Radiotherapy dosimetry based on perflourinated polymer optical fibers

Olusoji, Olugbenga J., Kam, Wern, O'Keeffe, Sinead

Olugbenga J. Olusoji, Wern Kam, Sinead O'Keeffe, "Radiotherapy dosimetry based on perflourinated polymer optical fibers," Proc. SPIE 11354, Optical Sensing and Detection VI, 113541W (1 April 2020); doi: 10.1117/12.2551148

Event: SPIE Photonics Europe, 2020, Online Only, France

RADIOTHERAPY DOSIMETRY BASED ON PERFLOURINATED POLYMER OPTICAL FIBRES

Olugbenga. J. Olusoji*, Wern Kam, Sinead. O'Keeffe
Optical Fibre Sensors Research Centre,
University of Limerick, Limerick, Ireland

ABSTRACT

The complexity of treating cancerous cells in patients using radiotherapy, requires precision in terms of the total dose received by the patient. The use of scintillating materials at the tip of the fibre for real time dosimetry dominate the current development of optical fibre dosimeters, however, they are limited to single point sensing. The changes in the structural and chemical properties in optical fibres on exposure to radiation gives rise to attenuation of the optical signal i.e. Radiation Induced Attenuation (RIA). This has proven to be a useful feature in monitoring radiation from gamma sources (Cobalt-60 sources) using PMMA (polymethyl methacrylate) fibres and perfluorinated graded-index polymer optical fibre (Cytop). The aim of this study is to investigate the performance of Cytop fibre in monitoring low doses of X-ray radiation (up to 10 Gy), produced by clinical linear accelerators (linac) for real time monitoring. The radiation induced attenuation (RIA) were measured across a 1 m length of Cytop fibre when the fibre was exposed to different radiation energy (6 MV, 10 MV) from the linac. The result of this study shows that the sensor has a good sensitivity of 0.0693 ± 0.004 dB/m/Gy and 0.0711 ± 0.004 dB/m/Gy at the wavelength of 695 nm and 817 nm respectively, for a radiation energy of 6 MV. Preliminary results demonstrate the potential of the Cytop fibre as a dosimeter for radiation treatment. The Cytop fibre sensor also exhibits a higher sensitivity, in the order of 3, when compared to PMMA optical fibres.

Keyword: Optical fibre, Cytop, Dosimetry, Radiation induced attenuation, Optical sensor, Radiotherapy

1. INTRODUCTION

The treatment of various forms of cancers have evolved over the years owing to research, increased awareness and improvement in detection. Various methods are employed to getting rid of the tumor cells, these include chemotheraphy, surgery and radiotherapy, with over half of the treated cases done with radiotherapy [1], [2]. The use of radiotherapy in treating the disease requires a precise control and confinement of the radioactive source to a certain locality because of their critical nature and proximity to other organs within the tumor cells. These complex treatments are done with the aid of a computerised Treatment Planning System (TPS) to determine the optimum target for the radiation and the associated dose to the tumour and the nearby organ at risk (OARs).

The characterisation of the radiation dose, involves the use of a radiation dosimeter. Types of dosimeter used for small field radiation sources includes the thermoluminiscent detector, diodes, metal-oxide semiconductor field effect transistors (MOSFETS), films, ionization chambers, electronic portal imagings (EPI) and plastic scintillating detector (PSD) [3], [4]. These dosimeters have certain shortcoming ranging from the stem effects in PSD to radioactive damage of MOSFET due to the accumulation of radiation dosage [3]. PSD of all the dosimeter took the center stage because of their flexibility and immunity to certain stray electromagnetic (EM) wave within the radiation bunker or treatment room as compared to solid-state detectors [4]. However, certain approach to having a multipoint sensor within the PSD using a PMMA fibre have not been able to achieve a large distribution. This is due to the limitation in the number of scintillating materials that can be placed within the fibre [5].

Perfluorinated (PF) polymer optical fibre (POF) based on cyclic transparent optical polymer (CYTOP) materials have shown to be sensitive to cobalt-60 sources [5]. The interaction of the gamma ray with the fibre material have been reported to induce an attenuation on the transmitted light in the fibre. The high magnitude of the radiation induced attenuation (RIA) observed over a large number of radiation dose qualifies it as a higly sensitive dosimetric material[5], [6].

*olugbenga.olusoji@ul.ie; phone +353(0)61-213 386; ofsrc.ul.ie

Optical Sensing and Detection VI, edited by Francis Berghmans, Anna G. Mignani, Proc. of SPIE
Vol. 11354, 113541W · © 2020 SPIE · CCC code: 0277-786X/20/$21 · doi: 10.1117/12.2551148

The focus of this research is to explore the sensitivity of the CYTOP fibre to an X-ray beam produced by a linac system, to push the development of the sensor for clinical dosimetry. The linac machine is commonly used for radiotherapy because of the stable form of radiation produced since they are not dependent on active radioactive sources that decay over time. The X-ray beam produced by a linac can also be modified for advance treatment techniques like intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc therapy (VMAT) with dose modulation [7]. The RIA produced in the fibre was characterised to a small quantity of radiation dose that falls within the total radiation dose delivered to patient in external beam radiotherapy.

1.1 Radiation-Induced Attenuation in Optical Fibres

The formation of radiation induced attenuation (RIA) in fibre is as a result of the molecular interaction of the fibre with the radiation. These interactions lead to the breaking of existing bonds and the formation of new bonds that are called colour centres. These color centers in polymer fibres are equivalent to free radicals which are generated by chain scission during irradiation [6]. Cytop are amorphous polymers and they are obtained from the cyclo-polymerization of perfluoro-3-butenyl-vinyl ether (PBVE) [8], although the reaction of this perflourinated polymer have not been extensively studied, there are indications that they behave like a polytetrafluoroethylene (PTFE) [9] and they majorly undergo chain scission upon irradiation in the presence of oxygen [10].

The evolution of the radiation induce attenuation can be evaluated with the Beer-Lambert law by considering the absorbance from the total length of the irradiated fibre. The RIA in the fibre is express in eqn 1.

$$RIA(dB) = -\frac{10}{L_0} log \left\{ \frac{P_T(\lambda, t)}{P_T^0(\lambda)} \right\} \qquad (1)$$

Where L_0 is the length of the irradiated fibre, $P_T(\lambda, t)$ is the optical power measured at end of the irradiated fibre and $P_T^0(\lambda)$ is the optical power measured before the fibre was irradiated [11].

2. EXPERIMENTAL PROCEDURE

In this work, a perfluorinated polymer optical fibre was used as a sensor to monitor the X-ray radiation produced by a linac machine. The perfluorinated fibre used (GigaPOF®-50SR) was produce by Chromis Technologies [12] with a Cytop core diameter of 50 µm (refractive index 1.355) and a Xylex cladding diameter of 490 µm (refractive index 1.342). Figure 1 illustrates the experimental setup where the perfluorinated fibre was irradiated with a 20 x 20 cm X-ray field produced by the Elekta Versa HD linear accelerator (linac) in the radiation bunker room at the Galway Clinic, Ireland. A 2 m length of Cytop fibre was attached to a 1 mm diameter PMMA fibre of approximately 20 m length to extend the fibre to the safe zone outside the irradiation room as illustrated in figure 1. A PMMA optical fibre was attached because they are readily available as compared to a preflorinated fibre. A SMA-SMA connector, filled with a refractive index matching gel to improve the coupling, was use to connect the Cytop and the PMMA fibres. An Ocean Optics LS-1 series tungsten halogen light source emitting at the VIS-Shortwave NIR range (360-1200 nm) was coupled to the Cytop fibre at one end, while the dital end of the PMMA optical fibre was connected to an Ocean Optics QE65000 spectrometer to measure the growth or decline of the transmited light across the fibre. The spectrometer was connected to a notebook PC and the analysis was carried out in real time with a customised LabVIEW software designed to monitor changes at four selected wavelengths. The scanning of the spectrum by the spectrometer was performed at an integration time of 1 sec for the first two reported experiment while the remaining were performed at an integration time of 100 msec. The curve was smoothened with a Savitzky-Golay filter at a polynomial order of 1 and a framelength of 7.

The beam profile of the radiation delivered by the linac machine can be categorised in two. The first category is the standard profile produced by the linac for treatment, which is a top hat profile and this is achieved by using a flattening filter to reshape the beam profile. This profile gives an even distribution of the energy across the exposed surface. The second category is the exposure done without a flattening filter i.e. a flattening filter free (FFF) regime, where the beam profile is like the combination of a guassian beam and a tophat beam. The FFF regime has a higher dose rate and are capable of delivering a more intense dose to localised region [7]. The sensitivity of the perfluorinated fibre to the two categories of radiation will be considered in this investigation.

The experiment starts with the exposure of 1 m length of the Cytop fibre to 10 Gy of Xray irradiation at an energy of 6 MV FF, 6 MV FFF and 10 MV FFF. A fibre length of 20 cm length was also considered. The results are further compared with the sensitivity of a 1 m length of PMMA fibre. The short term recovery of the fibre was also analysed.

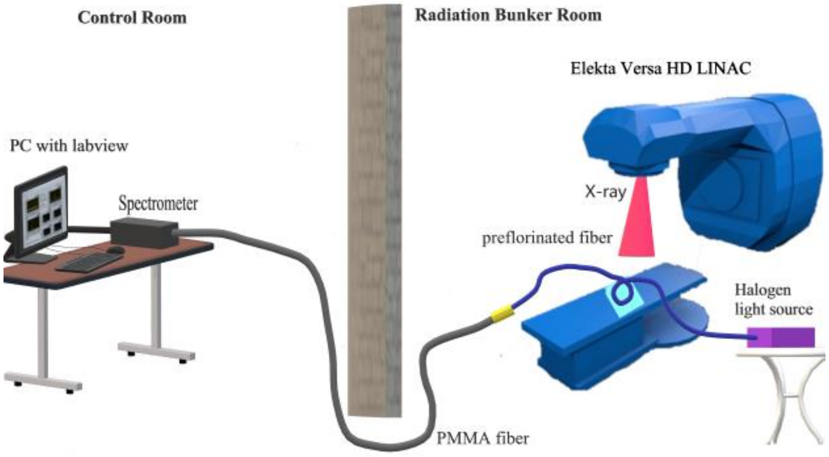


Figure 1. Setup of the experiment

3. RESULTS AND DISCUSSION

At the commencement of the experiment, a reference spectrum of the transmitted light was recorded with the customized LabVIEW software after the deduction of the dark spectrum. The continuous measurement of the spectrum at an integration interval of 1 sec, was initiated just before the linac shutter was switched on, to actively monitor the output changes of the fibre when exposed to irradiation. The fibre was exposed to a total irradiation dose of 10 Gy at an energy of 6 MV over a time period of 114 sec (dose rate 5.05 Gy/min) with a flatenning filter (FF). Figure 2(a) shows the spectra before irradiation and at 2 Gy intervals. The attenuation in the transmitted light through the fibre is clearly evident across the entire visible spectrum. There are specific wavelengths where the attenuation in the spectra is more prominent implying that the attenuation in the fibre is dependent on the wavelength. The magnitude of the dependence of the attenuation on wavelength is clearly shown in figure 2(b).

To further investigate the degradation level of the transmitted light in the fibre at specific wavelength, three maxima (580 nm, 695 nm and 817 nm) and one minima (756 nm) were selected as the focus wavelength of this inquiry. The measured intensity was converted to the radiation induced attenuation (dB) using equation 1. These wavelengths were selected as they show the most significant changes from the initial spectrum measured as a result of the influence of the radiation shown in figure 2(a). The evolution of the RIA was measured with specificity to the radiation dose. The degradation of the fibre with respect to radiation dose at individual wavelengths is shown in figure 2(b).

The Cytop fibre demonstrates a high sensitivity with a steady growth and a linear slope at the selected wavelengths. Within the span of the irradiation dose delivered to the fibre, no saturation of the RIA was observed. The sensitivity at each wavelength was calculated by considering the relationship between the RIA and the amount of radiation dose (Gy) received by the fibre sensor and is shown in figure 2(b). The sensitivity is wavelength dependant, demonstrating an increase in sensitivity with increasing wavelength, within the wavelength range monitored. A sensitivity of 0.0486 ± 0.006 dB/m/Gy, 0.0693 ± 0.004 dB/m/Gy, 0.0718 ± 0.004 dB/m/Gy and 0.0768 ± 0.004 dB/m/Gy was observed at a wavelength of 580 nm, 695 nm, 756 nm and 817 nm respectively. The fibre sensor exhibits highest sensitivity at the 817 nm wavelength when compared to other selected wavelengths, while the 580 nm wavelength of the fibre is least sensitive to the RIA.

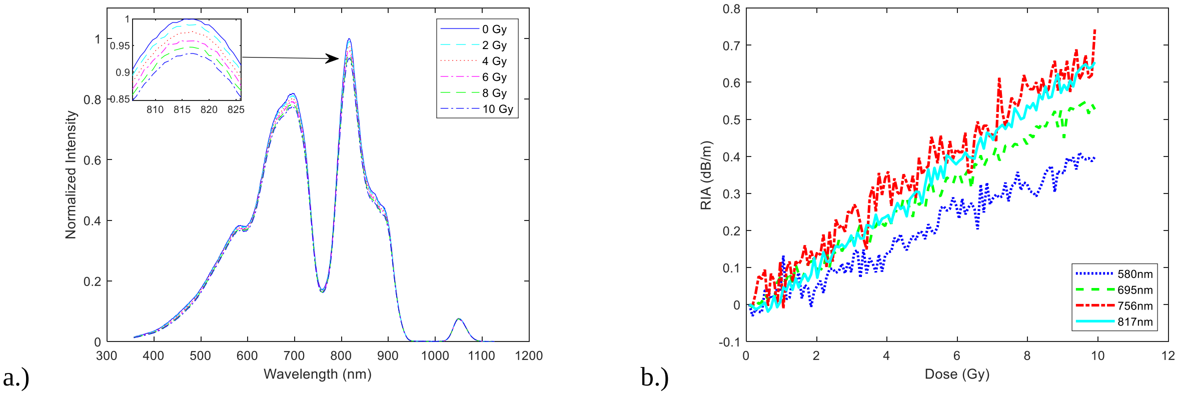


Figure 2. (a) Spectral of the transmited light before and after irradiation with 10 Gy and (b) Growth of the RIA with iradiation dose for selected wavelength at an energy of 6 MV.

To explore the sensitivity of the sensor to the second regime of the radiation produced by the linac, i.e flattening filter free, the fibre was exposed to a total dose of 10 Gy at a radiation energy of 6 MV and 10 MV and at a high dose rate of 14.44 Gy/min and 18.84 Gy/min respectively. The evolution of the RIA with respect to the irradiation dose is shown in figure 3. The sensitivity at 817 nm for radiation energy of 6 MV FFF and 10 MV FFF is 0.0586 ± 0.004 dB/m/Gy and 0.0578 ± 0.002 dB/m/Gy respectively. The sensitivity of the Cytop fibre to the flattening free regime is lower when compared to that with a flattening filter. The removal of a flattening filter increases the dose rate, softening the X-ray spectra and reduces the scattering from the head of the linac [13], thereby a higher RIA is expected. However, the lower sensitivity in the flattening filter regime by the Cytop fibre can be attributed to the positioning of the fibre loop around the guassian beam profile. The distribution of the radiation was uneven across the fibre and the fibre sensor was not capturing the center point of the beam with the highest energy.

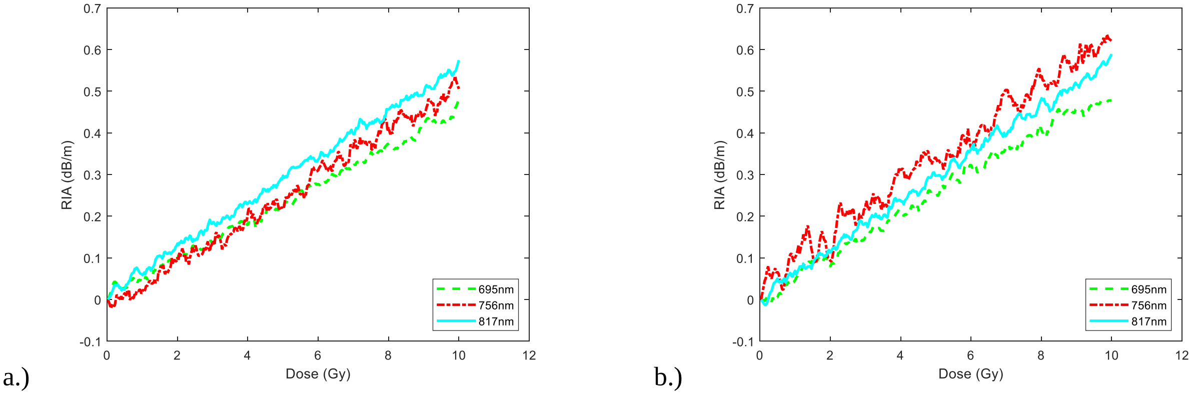
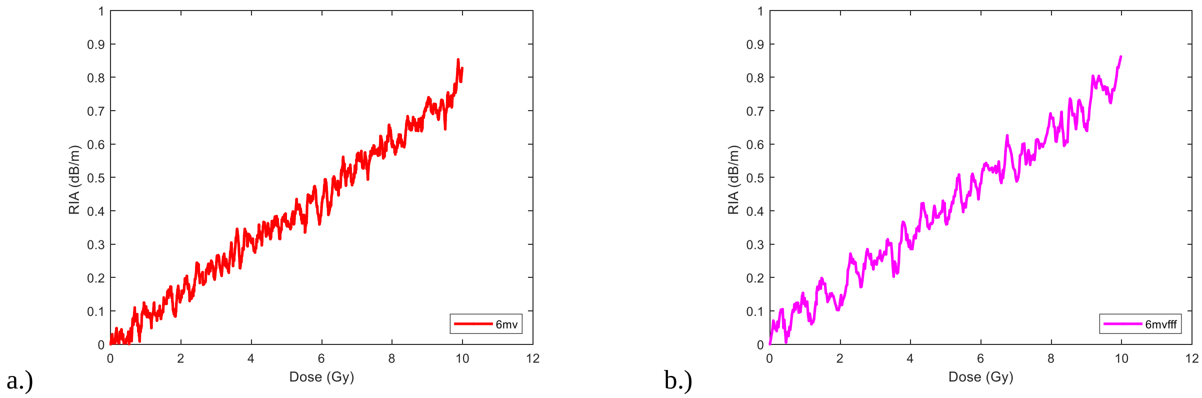


Figure 3. Growth of the RIA with respect to the radiation dose without a flattening filter (FFF) (a) 6 MV (b) 10 MV

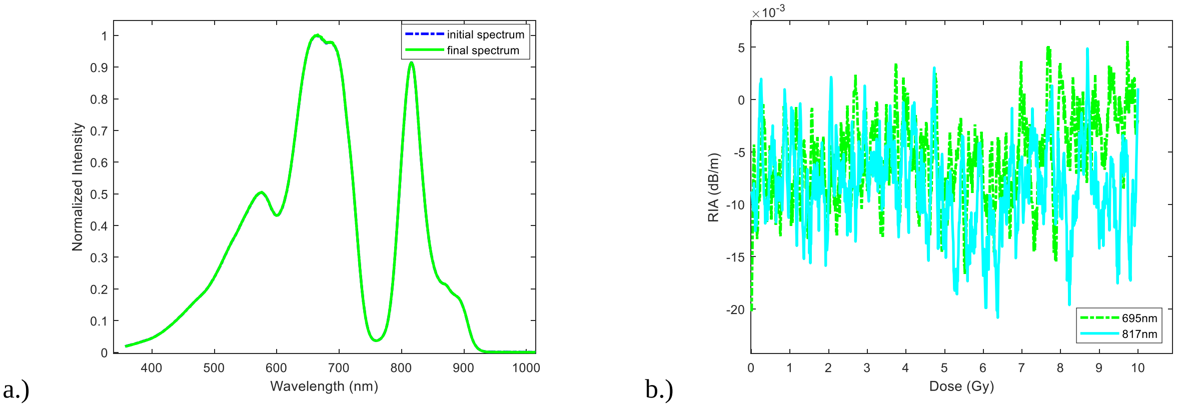
The application of the sensor as a coil of 1 m may not be applicable for measuring the radiation a patient receives during treatment. In considering the case where a spot in the tumour is expected to be treated, we explored the sensitivity of the fibre across the beam profile without forming a loop around the beam. A fibre length of 20 cm was laid across the beam to determine the sensitivity of the fibre to the radiation within a short length of fibre. A radiation energy of 6 MV with the flattening filter and 6 MV energy without the flattening filter was used for the irradiation of the fibre, a sensitivity of 0.0738 ± 0.005 dB/m/Gy and 0.0690 ± 0.01 dB/m/Gy was obtained for 6 MV and 6 MV FFF at the selected wavelength of 817 nm. The sensitivity was higher than that obtained in case of the 1 m coil because the fibre passes through the centre of the beam as oppose to loop around the centre of the beam. However, the sensitivity still fall within the range of uncertainty. The growth of the RIA with respect to the radiation dose is shown in figure 4 below.



a.) b.)

Figure 4. RIA for radiation dose for 20 cm of fibre (a) with flattening filter (b) flattening filter free

The RIA of the Cytop fibre was compared to that of a PMMA fibre using the same condition specified in the experiment i.e. a 1 m length of fibre within the same circumference of the fibre loop. The PMMA fibre shows little or no sensitivity to the radiation as illustrated in fig 5. A longer length of the PMMA fibre is required to observe the induced attenuation as reported by O'Keeffe *et al* [11] where a length of about 30 m was used to measure a small amount of the RIA in the PMMA fibre, a sensitivity of 0.001 dB/m/Gy was recorded.



a.) b.)

Figure 5. RIA for PMMA fibre (a) spectra representation (b) growth profile

Post-irradiation Recovery of the Fibre

The recovery process of the fibre after intense irradiation was also considered. There are certain scenarios where the fibre has to be re-irradiated during the treatment process, and so knowledge of the recovery is required to prevent the dosimeter from giving a false reading. The initial wavelength selected was also used to monitor the recovery time of the Cytop fibre. The evolution of the recovery of the fibre is shown in figure 6. The fibre recovered to a point of stability within 250 seconds, which open the possibility for the fibre dosimeter to be reusable after each measurement. The full recovery couldn't be explored on this occasion due to the time constraints of the measurement at the hospital.

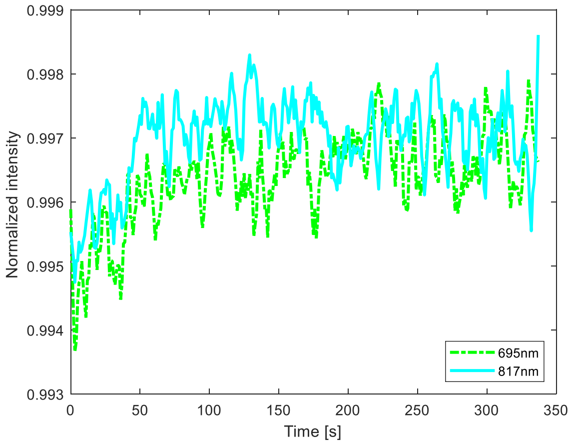


Fig 6. Recovery of the fibre after irradiation

CONCLUSIONS

The feasibility of a perfluorinated fibre as a dosimeter for external beam x-ray radiotherapy applications is investigated in this research. The radiation induced attenuation (RIA) in the fibre was the major effect considered in classifying the sensitivity of the fibre to the radiation source. The fibre was highly senstive to the irradiation of a 1 meter length of fibre at a wavelength of 817 nm, it showed a sensitivity of 0.0711 ± 0.004 dBm/Gy at an energy of 6 MV with the flattening filter. The sensitivity of the fibre to the irradiation of the fibre without a flattening filter was lower because of the positioning of the fibre around the x-ray beam. In general, the Cytop fibre demonstrates a higher sensitivity when compared to PMMA optical fibre which makes them a preferable option to operate as a dosimeter for x-ray radiation.

ACKNOWLEDGMENT

The authors would like to thank the Galway Clinic for the use of their facilities and to Peter Woulfe and Lauren Byrne for their assistance with the measurements. The authors would like to acknowledge the support of the Royal Society and Science Foundation Ireland, through the Royal Society – SFI University Research Fellowship, UF150618, and the Royal Society – SFI Enhancement Award, RGF\EA\180166.

REFERENCES

[1] C. M. Washington and D. T. Leaver, *Principles and practice of radiation therapy*, 2nd. editi. Mosby inc., 2004.

[2] D. E. Citrin, "Recent developments in radiotherapy," *N. Engl. J. Med.*, vol. 377, no. 11, pp. 1065–1075, 2017.

[3] A. Karellas and B. R. Thomadsen, *Scintillation Dosimetry*. CRC Press, Boca Raton, FL 33487-2742: , 2016.

[4] S. O'Keeffe *et al.*, "A review of recent advances in optical fibre sensors for in vivo dosimetry during radiotherapy," *Br. J. Radiol.*, vol. 88, no. 1050, 2015.

[5] P. Stajanca and K. Krebber, "Towards on-line radiation monitoring with perfluorinated polymer optical fibers," in *Proc.SPIE*, 2017, vol. 10323.

[6] P. Stajanca *et al.*, "Effects of gamma radiation on perfluorinated polymer optical fibers," *Opt. Mater. (Amst).*, vol. 58, pp. 226–233, 2016.

[7] B. J. Healy, D. van der Merwe, K. E. Christaki, and A. Meghzifene, "Cobalt-60 Machines and Medical Linear

Accelerators: Competing Technologies for External Beam Radiotherapy," *Clin. Oncol.*, vol. 29, no. 2, pp. 110–115, 2017.

[8] H. Teng, "Overview of the Development of the Fluoropolymer Industry," *Appl. Sci.*, vol. 2, no. 2, pp. 496–512, 2012.

[9] J. S. Forsythe and D. J. T. Hill, "Radiation chemistry of fluoropolymers," *Prog. Polym. Sci.*, vol. 25, no. 1, pp. 101–136, 2000.

[10] J. S. Forsythe, D. J. T. Hill, A. L. Logothetis, and A. K. Whittaker, "The radiation chemistry of the copolymer of tetrafluoroethylene with 2,2-bis(trifluoromethyl)-4,5-difluoro-1,3-dioxole," *Polym. Degrad. Stab.*, vol. 63, no. 1, pp. 95–101, 1999.

[11] S. O'Keeffe, E. Lewis, A. Santhanam, A. Winningham, and J. P. Rolland, "Low dose plastic optical fibre radiation dosimeter for clinical dosimetry applications," in *Proceedings of IEEE Sensors*, 2009, no. 978-1-4244–5335, pp. 1689–1692.

[12] "Active Optical Fibers | GigaPOF®-50SR |Chromis Fiberoptics.", https://chromisfiber.com/products/gigapof-50sr/. [Accessed: 19-Feb-2020].

[13] S. D. Sharma, "Unflattened photon beams from the standard flattening filter free accelerators for radiotherapy: Advantages, limitations and challenges," *J. Med. Phys.*, vol. 36, no. 3, pp. 123–125, Jul. 2011.